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13. ABSTRACT (Maximum 200 words)  The year 2 effort was divided between experimental characterization of the constitutive behavior of ferroelectric ceramics and reliability of actuators constructed from these materials. Key results of the study of the constitutive behavior under combined stress and electric field loading were the ability to obtain over 3000 microstrain from PZT without excessive hysteresis or cracking and the characterization of several compositions of PZT under high field and high stress loading. Key results under the reliability study were the development of a J-integral testing technique and a technique for the measurement of the displacement fields induced by electric field in front of a notch.				
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**Letter Report**  
**(01 April 1997 - 30 March 1998)**

**ONR GRANT/CONTRACT INFORMATION**

**Grant/Contract Title:** A Technique for Achieving 4000 Microstrain from PZT

**Performing Organization:** The Georgia Institute of Technology

**Principal Investigator:** Christopher S. Lynch

**Contract Number:** N000149610711

**PR Number:** 97PR02113-01

**ONR Scientific Officer:** Dr. Roshdy Barsoum

**DTIC QUALITY INSPECTED 3**

## **A Technique for Achieving 4000 Microstrain from PZT**

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### **Scientific Research Goals**

The research goals pursued during this period include the ability to operate piezoelectrics across switching thresholds without fatigue cracking, the continued development of a data base of high field material properties, and development of a fundamental understanding of fracture of ferroelectric ceramics.

### **Current Research Approach and Significant Research Findings**

#### *Operation across switching thresholds*

Operation across switching thresholds refers to an electric field driven switching in a material. This includes 90° domain switching in PZT, antiferroelectric to ferroelectric phase switching in PLSnZT, and tetragonal to rhombohedral switching in PZN single crystals. Operation across switching thresholds offers a significant increase in strain from strain-electric field coupled materials. The piezoelectric strain available from PZT is 1500 microstrain, but the switching strain is 3500 microstrain. The switching strain available from PLSnZT is near 5000 microstrain. The switching strain from PZN single crystals is over 10,000 microstrain.

The initial focus of this project was to operate PZT across switching thresholds. Experimental work has been performed on several compositions of PZT and on PLSnZT. Similar work will be performed on PZN single crystals in the near future.

#### **90° Domain switching in PZT**

A range of compositions obtained from Channel Industries and from TRS Ceramics have been characterized at high field and high stress. The materials from TRS ceramics were obtained as part of a DARPA sponsored actuator development program. The results from the Channel Industries materials are summarized in the 9/30/97 EOFYL. The results of the TRS Ceramics materials are discussed here.

**PZT 8:** The initial concept for practical use of 90° domain switching in PZT was to stabilize the domain structure of hard PZT in the 90° state, then use electric field to switch the structure to the 0° state. This concept did not work. The material was initially subjected to compressive stress parallel to the polarization. Switching was accompanied by cracking. Next, specimens were cut in shear mode so that the electric field would be 90° to the polarization direction. Again, when 90° switching began, the material cracked. Materials from three different sources were tried with the same result. When the electric field was below the switching threshold, the

PZT8 material gave a predominantly linear response from zero to 100 MPa. See Figure 1.

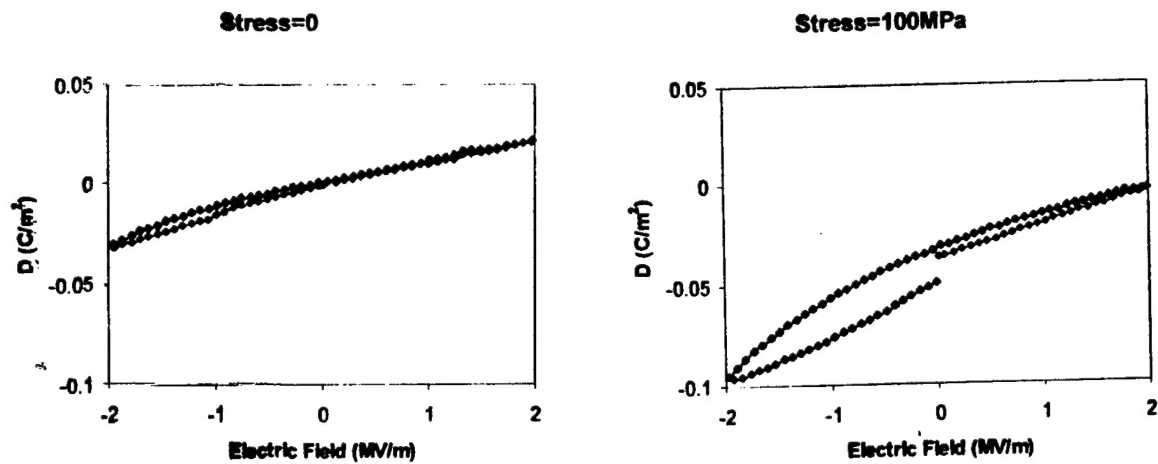


Figure 1. Strain/electric field response at zero and 100 MPa compressive stress levels.

**PZT 5H:** Operating the PZT 5H across switching thresholds was accomplished by preloading the material. The measured stress/strain response is shown in figure 2. There is an inflection point in the stress/strain curve at about 50 MPa. Next, the stress was held constant and the electric field cycled. At zero stress the electric field produced the classical butterfly loop. At 50 MPa, the electric field induced 3000 microstrain. The strain has not saturated at the electric field level used. Higher field levels should push the strain to 3500 microstrain. At 100 MPa, the strain is greatly reduced.

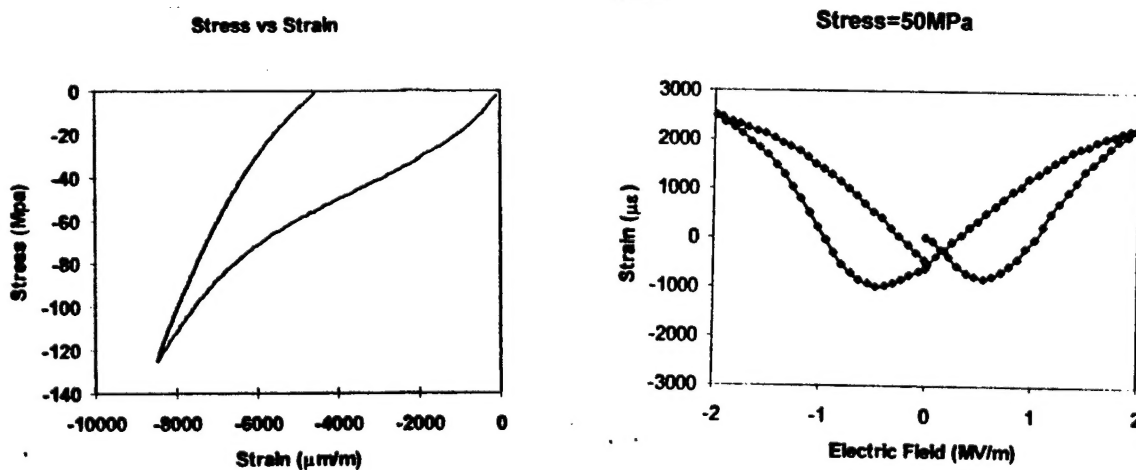


Figure 2. PZT 5H from TRS Ceramics operated across the 90° switching threshold produces over 3000 microstrain.

**PZT 5H FG:** Similar results were obtained with a fine grained material. In this case the strain was only 2500 microstrain. The potential advantage of the fine grained material may be a greater resistance to fracture and fatigue crack growth. Results are shown in Figure 3.

**PZT 5A and PMN-PT-LA:** PZT 5A and PMN-PT-LA were characterized at several stress levels. The results were less dramatic. The PZT 5A simply lost strain response as the stress increased. The quadratic electrostrictor went from 750 microstrain at zero stress to 500 microstrain at 100 MPa.

### **Reliability**

Reliability developments are based on fracture mechanics. These include experimental measurements based on the Vicker's indentation technique, a study of the mechanism of anisotropic crack growth in poled ferroelectrics, and development of the J-integral with application to test specimens. Results indicate that the electric field induced energy release rate is negative, and that the apparent "positive energy release rate" that is observed experimentally is actually a reduction of fracture toughness with electric field.

Reliability issues vary depending on the application and environment. For the ceramic itself, these issues include cracking of the ceramic, electrical breakdown of the ceramic, migration of the electrode material causing short circuit, and degradation of electro-mechanical coupling with temperature. In stack actuators these issues include all of the ceramic issues plus cracking at electrode edges, melting and diffusion of solder at temperatures below the Curie point, and softening or breakdown of epoxy insulation.

Recent work on the development of conjugate forms of the J-integral have led to the development of experimental techniques for determining the energy release rate based on measured load/displacement and voltage/charge curves. Due to problems with dielectric breakdown in the specimens, data are not yet available. These problems have been resolved and testing is ongoing.

Work has also been performed using a Moiré system to map the displacement fields in a notched piezoelectric specimen subjected to electric field. Again we have been struggling with the development of the technique and only have preliminary data.

### **Modeling**

The modeling effort has progressed to the point where we are able to determine the stress and electric field concentrations in front of an elliptical through flaw. The model uses a finite element formulation that calls a micromechanics based subroutine. Initial results are promising but

are limited to ellipses with impermeable interiors. This prevents us from shrinking the aspect ratio to the point that they truly look like cracks. Modifications to the code that will allow us to model flaws with finite permittivity interiors is nearing completion. This will allow simulation of the behavior of cracks.

#### **Relevance of Efforts to the Navy**

The results of this work are being applied in several Navy related programs.

##### **Data base of material properties at large field**

A Masters Thesis by Will Stoll, Georgia Tech, produced under this program is the first step toward development of a data base of large stress, large electric field properties. This data should lead to evaluation of coupling efficiency at large field levels. Application of the results include:

**Piezocomposites (Smart skins)**

**Vibration suppression (Ships and subs)**

**High power underwater acoustic sources**

Results have been provided to Raytheon Equipment Division (Acoustics engineering) for evaluation of sonobuoy design, and to United Technologies Research Center for device design evaluation.

##### **Improved reliability**

The results of this program should lead to improved device reliability. Understanding the relationship between polarization, grain size, and electro-mechanical coupling is a first step. Composition and grain size effects will be evaluated in the coming year.

##### **Higher strain capability**

Higher strain capability may come in the form of operating existing materials in a novel manner (across switching thresholds) or in the form of new materials like PZN single crystals. Larger strain further increases the need to understand fracture and develop means of controlling it. In the coming year, PZN single crystals will be evaluated in the Ga. Tech. servo-hydraulic system to determine their response under preload. Additional work with PZT 5H will be performed to determine the reliability of operation at 3000 microstrain.

## **List of Publications/Reports/Presentations**

### **1. Papers Published in Refereed Journals**

1. Lynch C. S. , "The Effect of Uniaxial Stress on the Electro-Mechanical Response of 8/65/35 PLZT", *Acta Mater.* 44(10), 4137-48 (1996)
2. C.S. Lynch, "Fracture of ferroelectric and relaxor electro-ceramics: influence of electric field", Accepted for publication, *Acta Materialia*, 6/97

### **(Manuscripts submitted to Journals:)**

1. H. Niu, J. Fan, C.S. Lynch, "Electric field effects on cracked ferroelectric ceramics", submitted to *J. Mat. Sci. Lett.* (1997)
2. W. Chen, C.S. Lynch, "A micro-electro-mechanical model for polarization switching of ferroelectric ceramics", submitted to *Acta Mater.* (1997)
3. C.S. Lynch, "J-Integral and fracture of ferroelectric ceramics", submitted to *International Journal of Solids and Structures* (3/98)
4. W. Chen, C.S. Lynch, "A model for simulating the constitutive behavior of anti-ferroelectric to ferroelectric phase changing ceramics." accepted with minor revisions *International Journal of Intelligent Systems and Structures* (sept. 1997)
5. J. Fan, W. Stoll, C.S. Lynch, "Non-linear Constitutive Behavior of Soft and Hard PZT: Experiments and Modeling", Submitted to Acta Materialia, (1998)
6. W. Chen, C.S. Lynch, "A nonlinear finite element method for ferroelectric ceramics", submitted to Journal of Mechanics and Physics of Solids, Feb (1998)

### **2. Non-Refereed Publications and Published Technical Reports**

1. Lynch, C.S. with W. Stoll, "Experimental Measurements of Electro-Mechanical Behavior of Four Compositions of PZT, *Proceedings of the 1996 IEEE International Symposium on the Application of Ferroelectrics*
2. Lynch, C.S. "J-Integral for Ferroelectric Compact Tension Specimens with Electric Field", *SPIE 1997 Symposium on Smart Structures and Materials* San Diego, Ca. Mar 1997
3. Lynch, C.S., "Annual report to the Office of Naval Research, A Technique for Achieving 4000 Microstrain from Hard PZT", Grant # N00014-96-1-0711
4. Lynch, C.S. "Quarterly Progress Report to TRS Ceramics / DARPA ACT Consortium" March 1998

### **3. Presentations**

#### **a. Invited**

1. Invited talk at the "Engineering adaptive composite structures symposium", technology overview presentation, Banff Canada 7/97
2. "Constitutive Behavior of Ferroelectric Ceramics", United Technologies Research Center, January (1998)

#### **b. Contributed**

1. "Stress/Strain/Electric Field Measurements on Hard and Soft PZT", *Materials Research Society*, Boston MA, Dec. 1996
2. "Constitutive laws for ferroelectric ceramics", *Penn State ONR annual review*, 5/97
3. "Stress/Electric-Field/Temperature Constitutive Behavior of Ferroelectric Crystals", *ONR Crystal Planning Workshop*, Washington DC, 5/97

### **4. Books (and sections thereof)**

1. Lynch, C.S., Strain Measurement Techniques, *The Measurements, Instrumentation, and Sensors Handbook*, A CRC Press, Inc. Publication, J.G. Webster ed., 1997

### **List of Honors/Awards**

<u>Name of Person Receiving Award</u>	<u>Recipient's Institution</u>	<u>Name, Sponsor, and Purpose of Award</u>
Christopher S. Lynch	The Georgia Institute of Technology	CAREER Award, National Science Foundation  Develop internal state variable based constitutive models of ferroelectric ceramics.

**Summary of FY 97**  
**Publications/Patents/Presentations/Honors/Participants**  
**(Number Only)**

		ONR Supported	Non ONR
a.	Number of Papers Submitted to Refereed Journals but Not Yet Published	__3__	__0__
b.	Number of Papers Published in Refereed Journals	__2__	__0__
c.	Number of Books or Chapters Submitted but not yet published	__0__	__1__
d.	Number of Books or Chapters Published	__0__	__0__
e.	Number of Printed Technical Reports and Non Refereed Papers	__2__	__1__
f.	Number of Patents Filed	__0__	__
g.	Number of Patents Granted	__0__	__
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings	__0__	__1__
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings	__2__	__1__
j.	Honors/Awards/Prizes for Contract/Grant Employees	__0__	__1__
k.	Number of Graduate Students and Post Docs Supported at least 25% this year on contract grant		
	Grad Students	__2__	__
	Total	__0__	__
	Female	__0__	__
	Minority	__0__	__
	post doc	__1__	__
	Total	__0__	__
	Female	__0__	__
	Minority	__0__	__
l.	Number of Female or Minority PIs of CO-PIs		
	New Female	__0__	__0__
	Continuing Female	__0__	__0__
	New Minority	__0__	__0__
	Continuing Minority	__0__	__0__